ELLIPSOMETER OR POLARIMETER AND THE LIKE SYSTEM WITH BEAM CHROMATIC SHIFTING AND DIRECTING MEANS

This Application Claims benefit of Provisional Application Serial No. 60/229,755 filed 09/05/00. This Application is also a Continuation-in-Part of Co-Pending Application 09/945,962 Filed 09/04/2001, and therevia of Applications: 09/517,125 Filed 02/29/2000; (now Patent 6,084,674); and of 09/246,888 filed 02/08/99, (now Patent 6,084,675); and further of: 09/225,118 (now Patent 6,084,674); 09/223,822 (now Patent 6,118,537); 09/232,257 (now Patent 6,141,102); 09/225,371 (now Patent 6,100,981); 09/225,076 (now Patent 5,963,325) which Applications depended from 08/997,311 filed 12/23/97, (now Patent 5,946,098). Further, via the 09/246,888 Application, this Application is a Continuation-In-Part of: 08/912,211 filed Aug. 15, 1997, (now Patent No. 5,872,630), which Continued-In-Part from 08/530,892 filed 09/20/95, (now Patent No. 5,666,201); and and is also a CIP of 08/618,820 filed 03/20/96, (now Patent No. 5,706,212). In addition, priority is Claimed from: 09/162,217 filed 09/29/98 via above Applications.

TECHNICAL FIELD

The disclosed invention relates to ellipsometer and polarimeter and the like systems and more particularly to ellipsometer and polarimeter and the like systems which comprise means for de-emphasising electromagnetic radiation source intensity in Visual wavelengths and simultaneously emphasizing intensity in both IR and UV wavelengths.

BACKGROUND

The practice of ellipsometry is well established as a

non-destructive approach to determining characteristics of sample systems, and can be practiced in real time. The topic is well described in a number of publications, one such publication being a review paper by Collins, titled "Automatic Rotating Element Ellipsometers: Calibration, Operation and Real-Time Applications", Rev. Sci. Instrum., 61(8) (1990).

In general, modern practice of ellipsometry typically involves causing a spectroscopic beam of electromagnetic radiation, in a known state of polarization, to interact with a sample system at at least one angle of incidence with respect to a normal to a surface thereof, in a plane of incidence. (Note, a plane of incidence contains both a normal to a surface of an investigated sample system and the locus of said beam of electromagnetic radiation and is measured in terms of a laboratory frame of reference). Changes in the polarization state of said beam of electromagnetic radiation which occur as a result of said interaction with said sample system are indicative of the structure and composition of said sample system. The practice of ellipsometry further involves proposing a mathematical model of the ellipsometer system and the sample system investigated by use thereof, and experimental data is then obtained by application of the ellipsometer system. This is typically followed by application of a square error reducing mathematical regression to the end that parameters in the mathematical model which characterize the sample system are evaluated, such that the obtained experimental data, and values calculated by use of the mathematical model, are essentially the same.

A typical goal in ellipsometry is to obtain, for each wavelength in, and angle of incidence of said beam of electromagnetic radiation caused to interact with a sample system, sample system characterizing PSI and DELTA values, (where

PSI is related to a change in a ratio of magnitudes of orthogonal components r_p/r_s in said beam of electromagnetic radiation, and wherein DELTA is related to a phase shift entered between said orthogonal components r_p and r_s), caused by interaction with said sample system:

$$PSI = |r_p/r_s|; \text{ and}$$

$$DELTA = (\Delta r_p - \Delta r_s).$$

As alluded to, the practice of ellipsometry requires that a mathematical model be derived and provided for a sample system and for the ellipsometer system being applied. In that light it must be appreciated that an ellipsometer system which is applied to investigate a sample system is, generally, sequentially comprised of:

a. a Source of a beam electromagnetic radiation;
b. a Polarizer element;

c. optionally a compensator element;

d. (additional element(s));

e. a sample system;

f. (additional element(s));

g. optionally a compensator element;

h. an Analyzer element; and
i. a Spectroscopic Detector System.

Each of said components b. - i. must be accurately represented by a mathematical model of the ellipsometer system along with a vector which represents a beam of electromagnetic radiation provided from said source of a beam electromagnetic radiation, identified in a. above)

Various conventional ellipsometer configurations provide that a Polarizer, Analyzer and/or Compensator(s) can be rotated during data acquisition, and are describe variously as Rotating Polarizer (RPE), Rotating Analyzer (RAE) and Rotating Compensator (RCE) Ellipsometer Systems. As described elsewhere in this Specification, another approach provides that no element be continuously rotated during data acquisition but rather that a sequence of discrete polarization states be imposed during data acquisition. This approach allows eliminating many costly components from conventional rotating element ellipsometer systems, and, hence, production of an "Ultra-Low-Cost" ellipsometer system. It is noted, that nulling ellipsometers also exist in which elements therein are rotatable in use, rather than rotating. Generally, use of a nulling ellipsometer system involves imposing a linear polarization state on a beam of electromagnetic radiation with a polarizer, causing the resulting polarized beam of electromagnetic radiation to interact with a sample system, and then adjusting an analyzer to an azimuthal azimuthal angle which effectively cancels out the beam of electromagnetic radiation which proceeds past the sample system. The azimuthal angle of the analyzer at which nulling occurs provides insight to properties of the sample system.

It is further noted that reflectometer systems are generally sequentially comprised of:

a. a Source of a beam electromagnetic radiation;

d. (optional additional element(s));

e. a sample system;

f. (optional additional element(s));

i. a Spectroscopic Detector System;

and that reflectometer systems monitor changes in intensity of a b am of electromagnetic radiation caused to interact with a sample system. That is, the ratio of, and phase angle between, orthogonal components in a polarized beam are not of direct concern.

Continuing, in use, data sets can be obtained with an ellipsometer system configured with a sample system present, sequentially for cases where other sample systems are present, and where an ellipsometer system is configured in a straight-through configuration wherein a beam of electromagnetic radiation is caused to pass straight through the ellipsometer system without interacting with a sample system. Simultaneous mathematical regression utilizing multiple data sets can allow evaluation of sample system characterizing PSI and DELTA values over a range of wavelengths. The obtaining of numerous data sets with an ellipsometer system configured with, for instance, a sequence of sample systems present and/or wherein a sequential plurality of polarization states are imposed on an electromagnetic beam caused to interact therewith, can allow system calibration of numerous ellipsometer system variables.

Patents of which the Inventor is aware include those to Woollam et al, No. 5,373,359, Patent to Johs et al. No. 5,666,201 and Patent to Green et al., No. 5,521,706, and Patent to Johs et al., No. 5,504,582 are disclosed for general information as they

pertain to ellipsometer systems.

Further Patents of which the Inventor is aware include Nos. 5,757,494 and 5,956,145 to Green et al., in which are taught a method for extending the range of Rotating Analyzer/Polarizer ellipsometer systems to allow measurement of DELTA'S near zero (0.0) and one-hundred-eighty (180) degrees, and the extension of modulator element ellipsometers to PSI'S of forty-five (45) degrees. Said Patents describes the presence of a variable, transmissive, bi-refringent component which is added, and the application thereof during data acquisition to enable the identified capability.

A Patent to Thompson et al. No. 5,706,212 is also disclosed as it teaches a mathematical regression based double Fourier series ellipsometer calibration procedure for application, primarily, in calibrating ellipsometers system utilized in infrared wavelength range. Bi-refringent, transmissive window-like compensators are described as present in the system thereof, and discussion of correlation of retardations entered by sequentially adjacent elements which do not rotate with respect to one another during data acquisition is described therein.

A Patent to He et al., No. 5,963,327 is disclosed as it describes an ellipsometer system which enables providing a polarized beam of electromagnetic radiation at an oblique angle-of-incidence to a sample system in a small spot area.

A Patent to Johs et al., No. 5,872,630 is disclosed as it describes an ellipsometer system in which an analyzer and polarizer are maintained in a fixed in position during data acquisition, while a compensator is caused to continuously rotate.

Patent to Dill et al., No. 4,953,232 is disclosed as it describes a rotating compensator ellipsometer system.

Patents co-owned with this Application, which Patents Claim various Compensator Designs recited in Claims herein, and which Patents are incorporated hereinto by reference are:

No. 5,946,098 to Johs et al.;
No. 5,963,325 to Johs et al.;
No. 6,084,674 to Johs et al.;
No. 6,084,675 to Herzinger et al.;
No. 6,100,981 to Johs et al.;
No. 6,118,537 to Johs et al.;
No. 6,141,102 to Johs et al.

Patents cited in examination of said Patents included No. 4,556,292 to Mathyssek et al. and No. 5,475,525 to Tournois et al.

A Patent to Coates et al., No. 4,826,321 is disclosed as it describes applying a reflected monochromatic beam of plane polarized electromagnetic radiation at a Brewster angle of incidence to a sample substrate to determine the thickness of a thin film thereupon. This Patent also describes calibration utilizing two sample substrates, which have different depths of surface coating.

Other Patents which describe use of reflected electromagnetic radiation to investigate sample systems are Nos. RE 34,783, 4,373,817, and 5,045,704 to Coates; and 5,452,091 to Johnson.

A Patent to Bjork et al., No. 4,647,207 is disclosed as it describes an ellipsometer system which has provision for

sequentially positioning a plurality of reflective polarization state modifiers in a beam of electromagnetic radiation. While said 207 Patent mentions investigating a sample system in a transmission mode, no mention or suggestion is found for utilizing a plurality of transmitting polarization state modifiers, emphasis added. Patent Nos. 4,210,401; 4,332,476 and 4,355,903 are also identified as being cited in the 207 Patent. It is noted that systems as disclosed in these Patents, (particularly in the 476 Patent), which utilize reflection from an element to modify a polarization state can, that if such an element is an essential duplicate of an investigated sample and is rotated ninety degrees therefrom, then the effect of the polarization state modifying element on the electromagnetic beam effect is extinguished by the sample.

A Patent to Mansuripur et al., No. 4,838,695 is disclosed as it describes an apparatus for measuring reflectivity.

Patents to Rosencwaig et al., Nos. 4,750,822 and 5,595,406 are also identified as they describe systems which impinge electromagnetic beams onto sample systems at oblique angles of incidence. The 406 Patent provides for use of multiple wavelengths and multiple angles of incidence. For similar reasons Patent No. 5,042,951 to Gold et al. is also disclosed.

A Patent to Osterberg, No. 2,700,918 describes a microscope, with variable means for increasing the visibility of optical images, partially comprised of discrete bi-refringent plates which can be positioned in the pathway between an eyepiece and an observed object. Other Patents identified in a Search which identified said 918 Patent are No. 3,183,763 to Koester; No. 4,105,338 to Kuroha; No. 3,992,104 to Watanabe and a Russian Patent, No. SU 1518728. Said other Patents are not believed to be particularly relevant, however.

A Patent, No. 5,329,357 to Bernoux et al. is also identified as it Claims use of fiber optics to carry electromagnetic radiation to and from an ellipsometer system which has at least one polarizer or analyzer which rotates during data acquisition. It is noted that if both the polarizer and analyzer are stationary during data acquisition that this Patent is not controlling where electromagnetic radiation carrying fiber optics are present.

A Patent to Chen et al., No. 5,581,350, is disclosed as it describes a method for regression calibration of ellipsometers.

As present invention preferred practice is to utilize a spectroscopic source of electromagnetic radiation with a relatively flat spectrum over a large range of wavelengths Patent No. 6,628,917 to Johs is disclosed. Patents relevant thereto include No. 5,179,462 to Kageyama et al. is identified as it provides a sequence of three electromagnetic beam combining dichroic mirrors in an arrangement which produces an output beam of electromagnetic radiation that contains wavelengths from each of four sources of electromagnetic radiation. Each electromagnetic beam combining dichroic mirror is arranged so as to transmit a first input beam of electromagnetic radiation, comprising at least a first wavelength content, therethrough so that it exits a second side of said electromagnetic beam combining dichroic mirror, and to reflect a second beam of electromagnetic radiation, comprising an additional wavelength content, from said second side of said electromagnetic beam combining dichroic mirror in a manner that a single output beam of electromagnetic radiation is formed which contains the wavelength content of both sources of electromagnetic radiation. The sources of electromagnetic radiation are described as lasers in said 462 Patent. Another Patent, No. 5,296,958 to Roddy et al., describes a similar system which utilizes Thompson Prisms to

similarly combine electromagnetic beams for laser source. Patents Nos. 4,982,206 and 5,113,279 to Kessler et al. and Hanamoto et al. respectively, describe similar electromagnetic electromagnetic beam combination systems in laser printer and laser beam scanning systems respectively. Another Patent, No. 3,947,688 to Massey, describes a method of generating tuneable coherent ultraviolet light, comprising use of an electromagnetic electromagnetic beam combining system. A Patent to Miller et al., No. 5,155,623, describes a system for combining information beams in which a mirror comprising alternating regions of transparent and reflecting regions is utilized to combine transmitted and reflected beams of electromagnetic radiation into a single output beam. A Patent to Wright, No. 5,002,371 is also mentioned as describing a beam splitter system which operates to separate "P" and "S" orthogonal components in a beam of polarized electromagnetic radiation.

In addition to the identified Patents, certain Scientific papers are also identified.

A paper by Johs, titled "Regression Calibration Method for Rotating Element Ellipsometers", Thin Solid Films, 234 (1993) is also disclosed as it describes a mathematical regression based approach to calibrating ellipsometer systems.

Another paper, by Gottesfeld et al., titled "Combined Ellipsometer and Reflectometer Measurements of Surface Processes on Nobel Metals Electrodes", Surface Sci., 56 (1976), is also identified.

A paper by Smith, titled "An Automated Scanning Ellipsometer", Surface Science, Vol. 56, No. 1. (1976), is also mentioned as it describes an ellipsometer system which does not require any moving, (eg. rotating), elements during data

acquisition.

Four additional papers by Azzam and Azzam et al. are also identified and are titled:

"Multichannel Polarization State Detectors For Time-Resolved Ellipsometry", Thin Solid Film, 234 (1993); and

"Spectrophotopolarimeter Based On Multiple Reflections In A Coated Dielectric Slab", Thin Solid Films 313 (1998); and

"General Analysis And Optimization Of The Four-Detector Photopolarimeter", J. Opt. Soc. Am., A, Vol. 5, No. 5 (May 1988); and

"Accurate Calibration Of Four-Detector Photopolarimeter With Imperfect Polarization Optical Elements", J. Opt. Soc. Am., Vol. 6, No. 10, (Oct. 1989);

as they describe alternative approaches concerning the goal of the present invention.

Even in view of the prior art, need remains for economical means for de-emphasising Visual wavelength intensity and simultaneously emphasizing both IR and UV wavelength intensities in ellipsometer, polarimeter and the like systems.

Further, there remains need for a spectroscopic ellipsometer system which:

presents with stationary polarizer and analyzer during data acquisition; and

utilizes a plurality of <u>transmissive</u> step-wise rotatable compensator means to effect a

plurality of sequential discrete, rather than continuously varying, polarization states during said data acquisition; and

which allows optional integrated combination with a reflectometer system via the sharing of a source of spectroscopic electromagnetic radiation and/or a spectroscopic multi-element detector system therewith.

In addition there remains need for a calibration procedure for a spectroscopic ellipsometer system which involves the gathering of spectroscopic data at a plurality of discrete polarization states for each of some number of sample systems. The present invention responds to said identified needs.

DISCLOSURE OF THE INVENTION

The disclosed invention comprises at least one electromagnetic radiation chromatic shifting beam directing means for intercepting a beam of electromagnetic radiation having a specific wavelength spectrum, and providing reflected electromagnetic radiation with a wavelength spectrum wherein the IR and UV wavelength intensities are emphasized. While any chromatic shifting reflective means which provides the result can be utilized, a particularly relevant readily available example is a Silicon Substrate with between about 500 and 1500 Angstroms of SiO_2 on its surface, said Silicon Substarte being positioned to receive electromagnetic radiation from, for instance, a Quartz halogen Source, (which provides an output wavelength spectrum wherein intensity is enphasized in the visual wavelength range), at an oblique angle. Said chromatic shifting reflective means provides a reflected wavelength spectrum with intensity of longer (ie. toward the IR), and shorter (ie. toward the UV), wavelengths increased, and with Visual wavelengths de-emphasized.

The reason the chromatic shifting electromagnetic beam reflective means provides utility is that gain in an amplifier in a spectrometer detector that receives electromagentic radiation conditioned thereby can be set higher when the intensity of the Visual Wavelength portion of the electromagnetic spectrum entered thereto is reduced. This increased gain is achieved without saturating the amplifier output response. Thus the increased spectrometer detector gain across the entire wavelength range can be beneficially applied to provide greater ssensitivity in the IR and UV range, as well as in maintaining such in the Visual range.

A disclosed invention method of providing a spectroscopic beam of electromagnetic radiation with more energy in IR and UV

wavelength ranges than is present in a source of spectroscopic electromagnetic radiation comprises the steps of:

a) providing a source of spectroscopic electromagnetic radiation and an electromagnetic radiation chromatic shifting beam directing means for use in reflectively directing a spectroscopic beam of electromagnetic radiation while de-emphasizing visual wavelength intensity and emphasizing both IR and UV wavelength intensities;

b) causing said source of spectroscopic electromagnetic radiation to provide a beam thereof and directing it to impinge upon said electromagnetic radiation chromatic shifting beam directing means at an oblique angle such that a reflected beam of electromagnetic radiation is produced, said chromatically shifted reflected beam of electromagnetic radiation having decreased intensity in visual wavelengths and increased intensity in IR and UV wavelengths.

The disclosed invention includes application of said electromagnetic radiation chromatic shifting beam directing means in a spectroscopic ellipsometer or polarimeter and the like. To so demonstrate, a new design for an ellipsometer system is disclosed as comprising:

a source of electromagnetic radiation;

Input Means comprising:

optical fiber;
coupler;
colimating lens;
beam directing mirror or beam chromatic shifting and directing means;

polarizer;
first rotatable compensator;

Sample Supporting Stage;

Output Means comprising:

second rotatable compensator;
analyzer;
beam directing mirror or beam chromatic shifting and directing means;
focusing lens;
spectrometer.

In operation the Source of electromagnetic radiation provides spectroscopic electromagnetic radiation to one end of said optical fiber, a second end thereof being secured in coupler. A beam of electromagnetic energy exiting said coupler is collimated by colimating lens and directed toward a selected beam directing mirror or beam chromatic shifting and directing means, from which it reflects. Said reflected beam is caused to pass through polarizer and the first rotatable compensator before being caused to impinge upon a sample which is held in position by said sample supporting stage. Electromagnetic radiation which reflects from said sample is directed to pass through second rotatable compensator and said analyzer before being caused to reflect from a selected beam chromatic shifting and directing means or a beam directing mirror, said reflected electromagnetic radiation is then caused to pass through focusing lens and enter spectrometer which comprises a multi-element detector system.

(It is noted that at least one chromatic shifting and directing means is selected to be present either before, after, or before and after the sample supporting stage).

A preferred embodiment of the disclosed invention provides for discrete manual Angle-of-Incidence manual setting of 65, 70, 75 and 90 degrees via positioning of the Input and Output Means, without need for tilt adjusting the Sample Supporting Stage, which is capable of receiving substrates of up to 8.5 inches in diameter. Said Sample Supporting Stage can be provided capability to automatically adjust position in the vertical "Z" direction. The input/output units have "home-sensors" present to enable easy setting of polarizer and analyzer positions. Typical spectral range is 360 to 380 through 1000nm and the preferred Spectrometer is available from Ocean Optics, (eg. Model USB2000). The overall size of a preferred design is conveniently about 19 inches wide, 10.5 inches tall and 15 inches deep. Mica or calcite waveplates can be used as retarders, as can compensators as described later in this Specification. And, it should be appreciated that the presence of two rotatable compensators makes it possible to determine all elements of a Mueller Matrix.

A disclosed invention method of investigating a sample comprises the steps of:

a) providing an ellipsometer system such as disclosed above, which comprises at least one chromatic shifting and directing means in the pathway of the beam;

b) while causing said source of electromagnetic radiation to provide a beam of spectroscopic electromagnetic radiation and interact with said sample and enter said spectrometer, causing at least one element selected from the group consisting of:

polarizer;
analyzer;
first rotatable compensator;

second rotatable compensator;

to be sequentially stepped through a progression of discrete polarization state setting positions, and at a plurality thereof taking data while all elements are stationary, said electromagnetic beam being also caused to reflect from said at least one chromatic shifting and directing means at some point between the source of electromagnetic radiation and said spectrometer.

Preferred practice involves holding the polarizer and analyzer stationary while sequentially rotating the first rotatable compensator and/or second rotatable compensator through a sequence of discrete positions.

It is also noted that use of the chromatic shifting and directing means is not limited to application in ellipsometer or polarimeter and the like systems in which a polarizer, analyzer, first compensator, second compensator or functionally similar element is/are stepped through a sequence of discrete polarization states, but can also be applied in such systems in which such elements are caused to continuously rotate during use and remain within the scope and bredth of the disclosed invention.

Further insight to spectroscopic ellipsometers in which the disclosed invention at least one chromatic shifting and directing means can be beneficially applied, is gleened from description substantially similar to what was previously disclosed in Co-Pending Application 09/945,962, from which this Application Continues-in-Part. Said 962 Application disclosed a spectroscopic ellipsometer system basically comprising:

a source of polychromatic electromagnetic radiation;

a polarizer which is fixed in position during data acquisition;
a stage for supporting a sample system;
an analyzer which is fixed in position during data acquisition; and
a multi-element spectroscopic detector system.

In addition, said ellipsometer system further comprises at least one means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation through a plurality of polarization states. The at least one means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation through a plurality of polarization states, is positioned between said polarizer and said stage for supporting a sample system, and/or and between said stage for supporting a sample system and said analyzer, and so that said beam of electromagnetic radiation transmits through a polarization state modifier element thereof in use. Said invention at least one means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation through a plurality of polarization states comprises a compensator which is mounted to allow step-wise rotation about the locus of a beam of electromagnetic radiation caused to pass therethrough.

While said invention can utilize essentially any Compensator, a preferred embodiment of the present invention provides that at least one of said at least one compensator(s), which is mounted to allow step-wise rotation about the locus of a beam of electromagnetic radiation caused to pass therethrough, be selected from the group consisting of:

a single element compensator;

a compensator system comprised of at least two per se. zero-order waveplates (MOA) and (MOB), said per se. zero-order waveplates (MOA) and (MOB) having their respective fast axes rotated to a position offset from zero or ninety degrees with respect to one another, with a nominal value being forty-five degrees;

a compensator system comprised of a combination of at least a first (ZO1) and a second (ZO2) effective zero-order wave plate, said first (ZO1) effective zero-order wave plate being comprised of two multiple order waveplates (MOA1) and (MOB1) which are combined with the fast axes thereof oriented at a nominal ninety degrees to one another, and said second (ZO2) effective zero-order wave plate being comprised of two multiple order waveplates (MOA2) and (MOB2) which are combined with the fast axes thereof oriented at a nominal ninety degrees to one another; the fast axes (FAA2) and (FAB2) of the multiple order waveplates (MOA2) and (MOB2) in said second effective zero-order wave plate (ZO2) being rotated to a position at a nominal forty-five degrees to the fast axes (FAA1) and (FAB1), respectively, of the multiple order waveplates (MOA1) and (MOB1) in said first effective zero-order waveplate (ZO1);

a compensator system comprised of a combination of at least a first (ZO1) and a second (ZO2) effective zero-order wave plate, said first (ZO1) effective zero-order wave plate being comprised of two multiple order waveplates (MOA1) and (MOB1) which are combined with the fast axes thereof oriented at a nominal ninety degrees to one another, and said second (ZO2) effective zero-order wave plate being comprised of two multiple order waveplates (MOA2) and (MOB2) which are combined with the fast axes thereof oriented at a nominal ninety degrees to one another; the fast axes (FAA2) and

(FAB2) of the multiple order waveplates (MOA2) and (MOB2) in said second effective zero-order wave plate (ZO2) being rotated to a position away from zero or ninety degrees with respect to the fast axes (FAA1) and (FAB1), respectively, of the multiple order waveplates (MOA1) and (MOB1) in said first effective zero-order waveplate (ZO1);

a compensator system comprised of at least one zero-order waveplate, ((MOA) or (MOB)), and at least one effective zero-order waveplate, ((ZO2) or (ZO1) respectively), said effective zero-order wave plate, ((ZO2) or (ZO1)), being comprised of two multiple order waveplates which are combined with the fast axes thereof oriented at a nominal ninety degrees to one another, the fast axes of the multiple order waveplates in said effective zero-order wave plate, ((ZO2) or (ZO1)), being rotated to a position away from zero or ninety degrees with respect to the fast axis of the zero-order waveplate, ((MOA) or (MOB));

(where the identifiers are shown in Figs. 10e - 10i).

Additional compensator systems, previously disclosed in Patent Application 08/997,311, (now Patent 5,946,098), and CIP's therefrom, which are specifically within the scope of the invention and can be included in the selection group are:

a compensator system comprised of a first triangular shaped element, which as viewed in side elevation presents with first and second sides which project to the left and right and downward from an upper point, which first triangular shaped element first and second sides have reflective outer surfaces; said retarder system further comprising a second triangular shaped element which as viewed in side elevation presents with first and second sides which project to the

left and right and downward from an upper point, said second triangular shaped element being made of material which provides reflective interfaces on first and second sides inside thereof; said second triangular shaped element being oriented with respect to the first triangular shaped element such that the upper point of said second triangular shaped element is oriented essentially vertically directly above the upper point of said first triangular shaped element; such that in use an input electromagnetic beam of radiation caused to approach one of said first and second sides of said first triangular shaped element along an essentially horizontally oriented locus, is caused to externally reflect from an outer surface thereof and travel along a locus which is essentially upwardly vertically oriented, then enter said second triangular shaped element and essentially totally internally reflect from one of said first and second sides thereof, then proceed along an essentially horizontal locus and essentially totally internally reflect from the other of said first and second sides and proceed along an essentially downward vertically oriented locus, then externally reflect from the other of said first and second sides of said first triangular shaped elements and proceed along an essentially horizontally oriented locus which is undeviated and undisplaced from the essentially horizontally oriented locus of said input beam of essentially horizontally oriented electromagnetic radiation even when said retarder is caused to rotate; with a result being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation;

a compensator system comprised of, as viewed in upright side elevation, first and second orientation adjustable mirrored elements which each have reflective surfaces; said compensator/retarder system further comprising a third element which, as viewed in upright side elevation, presents

with first and second sides which project to the left and right and downward from an upper point, said third element being made of material which provides reflective interfaces on first and second sides inside thereof; said third element being oriented with respect to said first and second orientation adjustable mirrored elements such that in use an input electromagnetic beam of radiation caused to approach one of said first and second orientation adjustable mirrored elements along an essentially horizontally oriented locus, is caused to externally reflect therefrom and travel along a locus which is essentially upwardly vertically oriented, then enter said third element and essentially totally internally reflect from one of said first and second sides thereof, then proceed along an essentially horizontal locus and essentially totally internally reflect from the other of said first and second sides and proceed along an essentially downward vertically oriented locus, then reflect from the other of said first and second orientation adjustable mirrored elements and proceed along an essentially horizontally oriented propagation direction locus which is essentially undeviated and undisplaced from the essentially horizontally oriented propagation direction locus of said input beam of essentially horizontally oriented electromagnetic radiation even when said compensator/retarder is caused to rotate; with a result being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation;

a compensator system comprised of a parallelogram shaped element which, as viewed in side elevation, has top and bottom sides parallel to one another, both said top and bottom sides being oriented essentially horizontally, said retarder system also having right and left sides parallel to one another, both said right and left sides being oriented at an angle to horizontal, said retarder being made of a

material with an index of refraction greater than that of a surrounding ambient; such that in use an input beam of electromagnetic radiation caused to enter a side of said retarder selected from the group consisting of: (right and left), along an essentially horizontally oriented locus, is caused to diffracted inside said retarder system and follow a locus which causes it to essentially totally internally reflect from internal interfaces of both said top and bottom sides, and emerge from said retarder system from a side selected from the group consisting of (left and right respectively), along an essentially horizontally oriented locus which is undeviated and undisplaced from the essentially horizontally oriented locus of said input beam of essentially horizontally oriented electromagnetic radiation even when said retarder is caused to rotate; with a result being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation;

a compensator system comprised of first and second triangular shaped elements, said first triangular shaped element, as viewed in side elevation, presenting with first and second sides which project to the left and right and downward from an upper point, said first triangular shaped element further comprising a third side which is oriented essentially horizontally and which is continuous with, and present below said first and second sides; and said second triangular shaped element, as viewed in side elevation, presenting with first and second sides which project to the left and right and upward from an upper point, said second triangular shaped element further comprising a third side which is oriented essentially horizontally and which is continuous with, and present above said first and second sides; said first and second triangular shaped elements being positioned so that a rightmost side of one of said first and second triangular

shaped elements is in contact with a leftmost side of the other of said first and second triangular shaped elements over at least a portion of the lengths thereof; said first and second triangular shaped elements each being made of material with an index of refraction greater than that of a surrounding ambient; such that in use an input beam of electromagnetic radiation caused to enter a side of a triangular shaped element selected from the group consisting of: (first and second), not in contact with said other triangular shape element, is caused to diffracted inside said retarder and follow a locus which causes it to essentially totally internally reflect from internal interfaces of said third sides of each of said first and second triangular shaped elements, and emerge from a side of said triangular shaped element selected from the group consisting of: (second and first), not in contact with said other triangular shape element, along an essentially horizontally oriented locus which is undeviated and undisplaced from the essentially horizontally oriented locus of said input beam of essentially horizontally oriented electromagnetic radiation even when said retarder is caused to rotate; with a result being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation;

a compensator system comprised of a triangular shaped element, which as viewed in side elevation presents with first and second sides which project to the left and right and downward from an upper point, said retarder system further comprising a third side which is oriented essentially horizontally and which is continuous with, and present below said first and second sides; said retarder system being made of a material with an index of refraction greater than that of a surrounding ambient; such that in use a an input beam of electromagnetic radiation caused to enter a side of said

retarder system selected from the group consisting of: (first and second), along an essentially horizontally oriented locus, is caused to diffracted inside said retarder system and follow a locus which causes it to essentially totally internally reflect from internal interface of said third sides, and emerge from said retarder from a side selected from the group consisting of (second and first respectively), along an essentially horizontally oriented locus which is undeviated and undisplaced from the essentially horizontally oriented locus of said input beam of essentially horizontally oriented electromagnetic radiation even when said retarder system is caused to rotate; with a result being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation; and

a compensator system comprised of first and second Berek-type retarders which each have an optical axes essentially perpendicular to a surface thereof, each of which first and second Berek-type retarders has a fast axis, said fast axes in said first and second Berek-type retarders being oriented in an orientation selected from the group consisting of: (parallel to one another and other than parallel to one another); said first and second Berek-type retarders each presenting with first and second essentially parallel sides, and said first and second Berek-type retarders being oriented, as viewed in side elevation, with first and second sides of one Berek-type retarder being oriented other than parallel to first and second sides of the other Berek-type retarder; such that in use an incident beam of electromagnetic radiation is caused to impinge upon one of said first and second Berek-type retarders on one side thereof, partially transmit therethrough then impinge upon the second Berek-type retarder, on one side thereof, and partially transmit therethrough such that a polarized beam of

electromagnetic radiation passing through both of said first and second Berek-type retarders emerges from the second thereof in a polarized state with a phase angle between orthogonal components therein which is different than that in the incident beam of electromagnetic radiation, and in a propagation direction which is essentially undeviated and undisplaced from the incident beam of electromagnetic radiation even when said retarder system is caused to rotate; with a result being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation;

a compensator system comprised of first and second Berek-type retarders which each have an optical axes essentially perpendicular to a surface thereof, each of which first and second Berek-type retarders has a fast axis, said fast axes in said first and second Berek-type retarders being oriented other than parallel to one another; said first and second Berek-type retarders each presenting with first and second essentially parallel sides, and said first and second Berek-type retarders being oriented, as viewed in side elevation, with first and second sides of one Berek-type retarder being oriented other than parallel to first and second sides of the other Berek-type retarder; such that in use an incident beam of electromagnetic radiation is caused to impinge upon one of said first and second Berek-type retarders on one side thereof, partially transmit therethrough then impinge upon the second Berek-type retarder, on one side thereof, and partially transmit therethrough such that a polarized beam of electromagnetic radiation passing through both of said first and second Berek-type retarders emerges from the second thereof in a polarized state with a phase angle between orthogonal components therein which is different than that in the

incident beam of electromagnetic radiation, and in a propagation direction which is essentially undeviated and undisplaced from the incident beam of electromagnetic radiation, said compensator system further comprising third and forth Berek-type retarders which each have an optical axes essentially perpendicular to a surface thereof, each of which third and forth Berek-type retarders has a fast axis, said fast axes in said third and forth Berek-type retarders being oriented other than parallel to one another, said third and forth Berek-type retarders each presenting with first and second essentially parallel sides, and said third and forth Berek-type retarders being oriented, as viewed in side elevation, with first and second sides of one of said third and forth Berek-type retarders being oriented other than parallel to first and second sides of said forth Berek-type retarder; such that in use an incident beam of electromagnetic radiation exiting said second Berek-type retarder is caused to impinge upon said third Berek-type retarder on one side thereof, partially transmit therethrough then impinge upon said forth Berek-type retarder on one side thereof, and partially transmit therethrough such that a polarized beam of electromagnetic radiation passing through said first, second, third and forth Berek-type retarders emerges from the forth thereof in a polarized state with a phase angle between orthogonal components therein which is different than that in the incident beam of electromagnetic radiation caused to impinge upon the first side of said first Berek-type retarder, and in a direction which is essentially undeviated and undisplaced from said incident beam of electromagnetic radiation even when said retarder system is caused to rotate; with a result being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation;

a compensator system comprised of first, second, third and forth Berek-type retarders which each have an optical axes essentially perpendicular to a surface thereof, each of which first and second Berek-type retarders has a fast axis, said fast axes in said first and second Berek-type retarders being oriented essentially parallel to one another; said first and second Berek-type retarders each presenting with first and second essentially parallel sides, and said first and second Berek-type retarders being oriented, as viewed in side elevation, with first and second sides of one Berek-type retarder being oriented other than parallel to first and second sides of the other Berek-type retarder; such that in use an incident beam of electromagnetic radiation is caused to impinge upon one of said first and second Berek-type retarders on one side thereof, partially transmit therethrough then impinge upon the second Berek-type retarder, on one side thereof, and partially transmit therethrough such that a polarized beam of electromagnetic radiation passing through both of said first and second Berek-type retarders emerges from the second thereof in a polarized state with a phase angle between orthogonal components therein which is different than that in the incident beam of electromagnetic radiation, and in a propagation direction which is essentially undeviated and undisplaced from the incident beam of electromagnetic radiation; each of which third and forth Berek-type retarders has a fast axis, said fast axes in said third and forth Berek-type retarders being oriented essentially parallel to one another but other than parallel to the fast axes of said first and second Berek-type retarders, said third and forth Berek-type retarders each presenting with first and second essentially parallel sides, and said third and forth Berek-type retarders being oriented, as viewed in side elevation, with first and second sides of one of said third

and forth Berek-type retarders being oriented other than parallel to first and second sides of said forth Berek-type retarder; such that in use an incident beam of electromagnetic radiation exiting said second Berek-type retarder is caused to impinge upon said third Berek-type retarder on one side thereof, partially transmit therethrough then impinge upon said forth Berek-type retarder on one side thereof, and partially transmit therethrough such that a polarized beam of electromagnetic radiation passing through said first, second, third and forth Berek-type retarders emerges from the forth thereof in a polarized state with a phase angle between orthogonal components therein which is different than that in the incident beam of electromagnetic radiation caused to impinge upon the first side of said first Berek-type retarder, and in a direction which is essentially undeviated and undisplaced from said incident beam of electromagnetic radiation even when said retarder system is caused to rotate; with a result being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation.

It is to be appreciated that said Compensator(s) can be caused to continuously rotate during data acquisition or be stepped through a series of discrete rotated positions and held stationary while obtaining data. Further, while not required, the present invention benefits from Compensator(s) designed to provide relatively constant, achromatic Polarization State Modification effects over a Spectroscopic range of wavelengths.

Where the polarizer in the spectroscopic ellipsometer system remains essentially fixed in position during data acquisition, it is noted that it is preferable that a source of electromagnetic radiation, and/or a present Polarizer or Polarization State Generator be positioned or configured so as to pass predominately

"S" Polarized electromagnetic radiation, as referenced to said beam combining system. The reason for this is that the split between "S" polarization transmission and reflection components is less, as a function of wavelength and electromagnetic beam angle-of-incidence to said beam combining means, when compared to that of the "P" components. The "P" component is far more affected, particularly around a Brewster angle condition, hence, where an "S" component, with reference to a beam combining system, is utilized, it is to be appreciated that variation in intensity of transmitted and reflected beams of electromagnetic radiation output from the beam combining system, as functions of wavelength and the angles of incidence of beams of electromagnetic radiation from sources of said transmitted and reflected beams of electromagnetic radiation, is minimized, as compared to variation which occurs in "P" components.

Before discussing the Method of Calibration of the discrete polarization state spectroscopic ellipsometer system, it is noted that the polarizer and analyzer thereof, which are essentially fixed in position during data acquisition, are not necessarily absolutely fixed in position between data acquisition procedures. Said polarizer and analyzer are preferably what is properly termed "Rotatable". That is they can be rotated to various positions by a user between data acquisitions, but they are not caused to be Rotating while data is being acquired. (Typical positioning of analyzer and polarizer azimuthal angles are plus or minus forty-five (+/-45) degrees).

Continuing, a method of calibrating a spectroscopic ellipsometer system comprising the steps of:

a. providing a spectroscopic ellipsometer system as described above herein;

said method further comprising, in any functional order, the steps of:

b. for each of at least two ellipsometrically different sample systems, obtaining at least one multi-dimensional data set(s) comprising intensity as a function of wavelength and a function of a plurality of discrete settings of said at least one means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation provided by said source of polychromatic electromagnetic radiation;

c. providing a mathematical model of thė ellipsometer system, including provision for accounting for the settings of said at least one means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation provided by said source of polychromatic electromagnetic radiation utilized in step b; and

d. by simultaneous mathematical regression onto said data sets, evaluating parameters in said mathematical model, including polarization state changing aspects of each of said plurality of discrete settings of said at least one means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation provided by said source of polychromatic electromagnetic radiation.

It is also mentioned that said method of calibrating a spectroscopic ellipsometer system can require, in the step b. obtaining of at least one multi-dimensional data set(s) comprising intensity as a function of wavelength and a function of a plurality of discrete settings of said at least one means for discretely, sequentially, modifying a polarization state of a beam of el ctromagnetic radiation, the obtaining of data from at

least as many sample systems as are utilized discrete settings of said at least one means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation provided by said source of polychromatic electromagnetic radiation. However, if characteristics of a means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation are parameterized, say as a function of wavelength, are expressed by equations with a minimized number of parameters therein, it is possible to reduce the number of sample systems which must be utilized. That is, parameterization can be beneficially applied.

The preferred embodiment of the present invention involves positioning input and output polarizer/analyzer system azimuthal angles at typical fixed, nominal, constant plus or minus forty-five (+/- 45) degrees, although use of polarizer and analyzer elements which are rotatable between data acquisition procedures is acceptable. It is noted that the static positioning of said input and output polarizer/analyzer system azimuthal angles greatly simplifies data acquisition, in that no phase sensors are required to detect rotational positioning are necessary, because synchronization is unnecessary. That is, as ellipsometric data is acquired asynchronously, the system requirements are greatly reduced as compared to ellipsometer systems which involve elements that are caused to rotate during data acquisition. Also, as alluded to, fiber optics are a preferred via for transporting electromagnetic radiation to and/or from the ellipsometer system.

It is again noted that a primary focus of the disclosed invention is the presence of an electromagnetic beam chromatic shifting and directing means for use in reflectively directing a

spectroscopic beam of electromagnetic radiation while de-emphasizing intensity in visual wavelengths and while simultaneously increasing both IR and UV wavelength intensities. While any functional element can be utilized, a preferred electromagnetic beam chromatic shifting and directing means comprises ailicon substrate with between 500 and 1500 Angstroms of silicon dioxide substantially uniformly present on a reflective surface thereof.

While the foregoing has disclosed a discrete polarization state setting spectroscopic ellipsometer/polarimeter system, it remains to describe the mathematical basis for practicing the invention. As described, the present Descrete Polarization State Spectroscopic Ellipsometer (DSP-SE_{tm}) system basically consists of a source of polychromatic electromagnetic radiation, an optical element for setting a polarization state, (eg. a polarizer), a stage for supporting a sample system with a sample system present thereupon, a means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation provided by said source of polychromatic electromagnetic radiation through a plurality of polarization states by passage therethrough, an analyzer, and a means for detecting beam intensity, (eg. a detector system). As indicated, in practice the input element is typically a polarizer with its transmission axis oriented approximately +45 or -45 degrees

degrees from the sample system plane of incidence. Using Mueller Matrix/Stokes Vector Calculus, the input beam passing through such a polarizer is represented by:

$$I_P = \begin{pmatrix} 1 \\ \cos(2P) \\ \sin(2P) \\ 0 \end{pmatrix}$$

where "P" is the azimuthal angle of the polarizer with respect to the sample plane of incidence. For optimal performance over a wide range of sample systems, and computational simplicity, the "P" is usually chosen to be +/- 45 degrees, and the Stokes Vector becomes:

$$I_P = \begin{pmatrix} 1 \\ 0 \\ \pm 1 \\ 0 \end{pmatrix}$$

Now, an isotropic sample can be optically modeled by the Mueller Matrix:

$$M_S = \begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{pmatrix}$$

and the Stokes Vector resulting from a polarized polychromatic electromagnetic radiation beam interaction with a sample system is described by:

$$M_S \cdot I_P = \begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \\ \pm 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ -N \\ C \cdot \pm 1 \\ -S \cdot \pm 1 \end{pmatrix}$$

A generalized polarization state modifier (PSM) element, (which can comrpise a combination of elements), followed by a

polarization state insensitive detector yields the following Stokes Vector:

$$PSM = (1\ \ 0\ \ 0\ \ 0)\cdot\begin{pmatrix} m00 & m01 & m02 & m03 \\ m10 & m11 & m12 & m13 \\ m20 & m21 & m22 & m23 \\ m30 & m31 & m32 & m33 \end{pmatrix} = (m00\ \ m01\ \ m02\ \ m03)$$

therefore, if there are "n" discrete polarization states, the beam intensity measured for the "n'th" polarization state is:

$$I_n = PSM_n \cdot M_S \cdot I_P = \left(m0_n\ \ m1_n\ \ m2_n\ \ m3_m\right)\cdot\begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{pmatrix}\cdot\begin{pmatrix} 1 \\ 0 \\ \pm 1 \\ 0 \end{pmatrix} = m0_n - m1_n \cdot N + \left(m2_n \cdot C - m3_m \cdot S\right)\cdot \pm 1$$

The transfer matrix for traditional 4-detector polarimeter systems is constructed by inserting the (PSM) into "rows" which correspond to the polarization state measured by each detector:

$$I_n = A \cdot S \qquad \begin{pmatrix} I_0 \\ I_1 \\ I_2 \\ I_3 \end{pmatrix} = \begin{pmatrix} m0_0 & m1_0 & m2_0 & m3_0 \\ m0_1 & m1_1 & m2_1 & m3_1 \\ m0_2 & m1_2 & m2_2 & m3_2 \\ m0_3 & m1_3 & m2_3 & m3_3 \end{pmatrix}\cdot\begin{pmatrix} 1 \\ -N \\ C \cdot \pm 1 \\ -S \cdot \pm 1 \end{pmatrix}$$

If the "A" transfer matrix is invertable, (ie. the determinate is non-zero), it can be concluded that sample system's N, C and S ellipsometric parameters can be determined from the measured intensities at each detector.

$$\begin{pmatrix} 1 \\ -N \\ C \cdot \pm 1 \\ -S \cdot \pm 1 \end{pmatrix} = A^{-1}\cdot\begin{pmatrix} I_0 \\ I_1 \\ I_2 \\ I_3 \end{pmatrix}$$

Furthermore, in a traditional 4-detector polarimeter system, the

"A" transfer matrix is determined, (at each wavelength of operation), by inputting a series of known polarization states and measuring the resulting intensities at each detector.

While the present invention ($DSP-SE_{tm}$) is similar to traditional 4-detector polarimeter systems, it differs in that more than 4 polarization states can optionally be incorporated into the measurement. The "A" matric therefore is generally not "square", and a simple inversion can not be used to directly extract sample system N, C and S ellipsometic parameters. Regression analysis based on known optical models can also be used to determine, (ie. calibrate), the "A" transfer matrix of the system, and to extract the ellipsometric parameters from the "n" measuremed intensities.

While many variations are possible, in the preferred, non-limiting, embodiment of the present invention the ($DSP-SE_{tm}$) the input polarizer, as mentioned, is fixed at 45 degrees, such that the Stokes Vector which enters the polarimeter after interaction with the sample system is given by:

$$M_S \cdot I_P = k \cdot \begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} = k \cdot \begin{pmatrix} 1 \\ -N \\ C \\ -S \end{pmatrix}$$

(where "k" is an arbitrary constant which accounts for the unknown intensity provided by the source of polychromatic electromagnetic radiation).

For the 1st discrete polarization state of the detector system, a polarizer, (typically termed an analyzer when placed after the sample system), with the azimuthal angle threof set at

45 degrees, the detected intensity is of the form:

$$I_0 = PSM_0 \cdot M_S \cdot I_P = (1 \ \ 0 \ \ -1 \ \ 0) \cdot k \cdot \begin{pmatrix} 1 \\ -N \\ C \\ -S \end{pmatrix} = k \cdot (1 - C)$$

For the next two discrete polarization states, a quarter-wave retarder can be inserted in front of the analyzer, at azimuthal angles of zero (0.0) and ninety (90) degrees respectively, to provide:

$$I_1 = PSM_1 \cdot M_S \cdot I_P = (1 \ \ 0 \ \ -1 \ \ 0) \cdot \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \cdot k \cdot \begin{pmatrix} 1 \\ -N \\ C \\ -S \end{pmatrix} = k \cdot (1 + S) \qquad \text{(for retarder @ 0°)}$$

$$I_2 = PSM_2 \cdot M_S \cdot I_P = (1 \ \ 0 \ \ -1 \ \ 0) \cdot \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \cdot k \cdot \begin{pmatrix} 1 \\ -N \\ C \\ -S \end{pmatrix} = k \cdot (1 - S) \qquad \text{(for retarder @ 90°)}$$

For two additional discrete polarization states, a quarter-wave retarder can be inserted in front of the analyzer, at azimuthal angles of +/- twenty-two (22) degrees, respectively, to provide:

$$I_3 = PSM_3 \cdot M_S \cdot I_P = (1 \ \ 0 \ \ -1 \ \ 0) \cdot \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} & \frac{-1}{2} \cdot \sqrt{2} \\ 0 & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \cdot \sqrt{2} \\ 0 & \frac{1}{2} \cdot \sqrt{2} & \frac{-1}{2} \cdot \sqrt{2} & 0 \end{pmatrix} \cdot k \cdot \begin{pmatrix} 1 \\ -N \\ C \\ -S \end{pmatrix} = \left(1 - \frac{1}{2} \cdot C + \frac{1}{2} \cdot N + \frac{1}{2} \cdot \sqrt{2} \cdot S\right) \cdot k$$

(for retarder @ +22.5°)

$$I_4 = PSM_4 \cdot M_S \cdot I_P = (1\ \ 0\ \ -1\ \ 0)\cdot\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{-1}{2} & \frac{1}{2}\cdot\sqrt{2} \\ 0 & \frac{-1}{2} & \frac{1}{2} & \frac{1}{2}\cdot\sqrt{2} \\ 0 & \frac{-1}{2}\cdot\sqrt{2} & \frac{-1}{2}\cdot\sqrt{2} & 0 \end{pmatrix}\cdot k\cdot\begin{pmatrix} 1 \\ -N \\ C \\ -S \end{pmatrix} = \left(1 + \frac{1}{2}\cdot\sqrt{2}\cdot S - \frac{1}{2}\cdot N - \frac{1}{2}\cdot C\right)\cdot k$$

(for retarder @ -22 5°).

Simple combinations of these intensities yield:

$$I_0 = k\cdot(1 - C) \qquad I_1 - I_2 = 2\cdot k\cdot S \qquad I_1 + I_2 = 2\cdot k \qquad I_3 - I_4 = k\cdot N$$

from which sample system N, C, S, and are easily derived as:

$$N = 2\cdot\frac{I_3 - I_4}{I_1 + I_2} \qquad C = \frac{(I_1 + I_2 - 2\cdot I_0)}{(I_1 + I_2)} \qquad S = \frac{(I_1 - I_2)}{(I_1 + I_2)}$$

$$\Delta = \mathrm{atan}\left(\frac{S}{C}\right) \qquad \Psi' = \frac{1}{2}\cdot\mathrm{atan}\left(\frac{\sqrt{C^2 + S^2}}{N}\right)$$

While the math for the preceeding 5-state (DSP-SE$_{tm}$) system is elegant, a potential difficulty in implementing said design is that insertion of the quarter-wave plates to effect polarization states 1 - 4, introduces intensity loss as a result of reflection from the optical element surface, which is not present when obtaining the first data set wherein no quarter-wave plate is present. This additional intensity loss must be accounted for in the calibration algorithm. A modified approach involves not obtaining or not utilizing the first data set. While this slightly complicates the equations, a simple analytic solution is still possible and values for N, C and S can be derrived as:

$$I_1 - I_2 = 2\cdot k\cdot S \qquad I_1 + I_2 = 2\cdot k \qquad I_3 - I_4 = k\cdot N \qquad I_3 + I_4 = \left(2 - C + \sqrt{2}\cdot S\right)\cdot k$$

$$N = 2\cdot\frac{(I_3 - I_4)}{(I_1 + I_2)} \qquad C = \frac{\left(2 - \sqrt{2}\right)\cdot I_2 + \left(2 + \sqrt{2}\right)\cdot I_1 - 2\cdot(I_3 + I_4)}{(I_1 + I_2)} \qquad S = \frac{(I_1 - I_2)}{(I_1 + I_2)}$$

A more general 4-state (DSP-SE$_{tm}$) approach utilizes an input polarizer, an output analyzer and four (4) retarder elements at various azimuthal orientations. In this approach, while the azimuthal orientations for the optical elements are nominally chosen to be the same as in the preceeding design, arbitrary azimuthal orientations as well as non-ninety degree retardation values are allowed. Under this approach, the Stokes Vector provided to the Polarimeter is given by:

$$I_{S,P} = \begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{pmatrix} \cdot \begin{pmatrix} 1 \\ \cos(2P) \\ \sin(2P) \\ 0 \end{pmatrix} = \begin{pmatrix} 1 - N\cdot\cos(2\cdot P) \\ -N + \cos(2\cdot P) \\ C\cdot\sin(2\cdot P) \\ -S\cdot\sin(2\cdot P) \end{pmatrix} = \begin{pmatrix} s0 \\ s1 \\ s2 \\ s3 \end{pmatrix} \qquad \text{(DPS \#1)}$$

(where "P" is the input polarimeter azimuth).

The response of each discrete polarization state "n" to an input Stokes Vector is:

$$I_n = \begin{pmatrix} m0_n & m1_n & m2_n & m3_n \end{pmatrix}$$

$$m0_n = 1$$

$$m1_n = \left(cr_n\cdot sr_n - c\delta_n\cdot sr_n\cdot cr_n\right)\cdot S2A + \quad \left(cr_n\right)^2 + c\delta_n\cdot\left(sr_n\right)^2 \quad \cdot C2A \qquad \text{(DPS \#2)}$$

$$m2_n = \left[\left(sr_n\right)^2 + c\delta_n\cdot\left(cr_n\right)^2\right]\cdot S2A + \left(sr_n\cdot cr_n - c\delta_n\cdot cr_n\cdot sr_n\right)\cdot C2A$$

$$m3_n = (S2A\cdot cr - C2A\cdot sr)\cdot s\delta$$

where cr=cos(2r), sr=sin(2r), cδ=cos(δ), sδ=sin(δ), C2A=cos(2A), S2A=sin(2A), r is the retarder azimuthal orientation angle, δ is the retardance, and A is the analyzer orientation.

(for most retarders, the retardance varies inversely with wavelength, that is $\delta(\lambda) = \delta_o/\lambda$)

These polarization state modifying vectors can be packed into a (4 x 4) square transfer matrix "A", such that the measured intensity for each discrete state is given by:

$$I_n = A\cdot I_{S,P} \qquad \begin{pmatrix} I_0 \\ I_1 \\ I_2 \\ I_3 \end{pmatrix} = \begin{pmatrix} m0_0 & m1_0 & m2_0 & m3_0 \\ m0_1 & m1_1 & m2_1 & m3_1 \\ m0_2 & m1_2 & m2_2 & m3_2 \\ m0_3 & m1_3 & m2_3 & m3_3 \end{pmatrix} \cdot \begin{pmatrix} s0 \\ s1 \\ s2 \\ s3 \end{pmatrix}$$

To determine the Stokes Vector incident on the Polarimeter, the transfer matrix "A" s inverted and multiplied times the measured intensities coresponding to each discrete polarization state:

$$\begin{pmatrix} s0 \\ s1 \\ s2 \\ s3 \end{pmatrix} = \begin{pmatrix} m0_0 & m1_0 & m2_0 & m3_0 \\ m0_1 & m1_1 & m2_1 & m3_1 \\ m0_2 & m1_2 & m2_2 & m3_2 \\ m0_3 & m1_3 & m2_3 & m3_3 \end{pmatrix}^{-1} \cdot \begin{pmatrix} I_0 \\ I_1 \\ I_2 \\ I_3 \end{pmatrix}$$

and the sample system parameters:

$$N = cos(2 \cdot P) - s1 \qquad C = \frac{s2}{\sin(2 \cdot P)} \qquad S = \frac{-s3}{\sin(2 \cdot P)}$$

can then be extracted. To illustrate this approach, a transfer matrix is constructed assuming nominal azimuthal orientations of (0.0), (90) (+22.5) and (-22.5) degrees for each of the four (4) discrete polarization states. The same nominal retardance is assumed for each retarder. The analytical inversion of this matrix is very complicated, but it is still trivial to numerically invert the matrix given the sample expressions for each element given by:

$$A = \begin{bmatrix} 1 & C2A & c\delta \cdot S2A & S2A \cdot s\delta \\ 1 & C2A & c\delta \cdot S2A & -(S2A \cdot s\delta) \\ 1 & (1 - c\delta) \cdot \frac{S2A}{2} + (1 + c\delta) \cdot \frac{C2A}{2} & (1 + c\delta) \cdot \frac{S2A}{2} + (1 - c\delta) \cdot \frac{C2A}{2} & (S2A - C2A) \cdot s\delta \cdot \frac{\sqrt{2}}{2} \\ 1 & -(1 - c\delta) \cdot \frac{S2A}{2} + (1 + c\delta) \cdot \frac{C2A}{2} & (1 + c\delta) \cdot \frac{S2A}{2} - (1 - c\delta) \cdot \frac{C2A}{2} & (S2A + C2A) \cdot s\delta \cdot \frac{\sqrt{2}}{2} \end{bmatrix}$$

Multiplying the inverted matrix by the measured intensities for each discrete polarization state allows straight forward determination of the sample system characterizing N, C, S, ψ, and Δ.

A General Regression Based Approach to Calibration of ($DSP-SE_{tm}$) systems and allow extraction of accurate ellipsometric sample system characterizing data assumes that the ($DSP-SE_{tm}$) system measures polychromatic electromagnetic radiation beam intensity at "n" discrete polarization states, and that "m" samples with different ellipsometric properties are utilized. For a traditional polarimeter system, which is calibrated on a wavelength by wavelength basis, it is necessary to have "m" be greater than or equal to "n". However, utilizing global regression which allows calibration parameters to be parameterized vs. wavelength, (thereby reducing the number of parameters required to describe the system transfer Matrices "A" at each wavelength), it is possible to reduce the number of calibration sample systems required, "m", to be less than "n". Under this approach, calibration of a present invention ($DSP-SE_{tm}$) system, a multi-dimensional data set "I" is measured consisting of measured polychromatic electromagnetic radiation beam intensities for each discrete polarization state, on each calibration sample system, and at each wavelength in the spectral range of the instrument:

$$Igen(p_y)_{i,j,k} = A \cdot \begin{pmatrix} 1 & -N_{j,k} & 0 & 0 \\ -N_{j,k} & 1 & 0 & 0 \\ 0 & 0 & C_{j,k} & S_{j,k} \\ 0 & 0 & -S_{j,k} & C_{j,k} \end{pmatrix} \cdot \begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix}$$

To generate "predicted" intensities measured by the ($DSP-SE_{tm}$), (as a function of calibration parameters spsecified in the vector p_y), the following equation is applied:

$Iexp_{i,j,k}$	where	$i = 1 \ldots n$	(for each discrete polarization state)
		$j = 1 \ldots m$	(for each calibration sample)
		$k = 1 \ldots w$	(for each wavelength)

where "A" is an ("n" x 4) matrix, in which each row is possibly parameterized by foregoing equation DSP#2 and the input vector s_n is possibly parameterized by the input polarizer azimuth by an equation DSP#1. The extraction of calibration sample system's N, C and S parametres can be calculated as a function of film thickness and angle of incidence (given calibration sample systems which are well characterized by known optical models and optical constants, such as SiO_2 on Si films with systematically increasing SiO_2 film thicknesses).

To perform regression analysis, the "chi-squared" function:

$$\chi^2=\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{w}\left[\frac{Iexp_{i,j,k}}{\sqrt{\sum_{i=1}^{m}\left(Iexp_{i,j,k}\right)^2}}-\frac{Igen(p_y)_{i,j,k}}{\sqrt{\sum_{i=1}^{m}\left(Igen(p_y)_{i,j,k}\right)^2}}\right]^2$$

is then minimized, (typically utilizing a non-linear regression algorithm such as "Marquard-Levenberg"), by adjusting calibration parameters specified in the vector "p_y". To aid in the regression, both the experimental and generated intensity vectors are normalized by the sum of the squares of all the discrete polarization states at each wavelength.

If the global parameterization of calibration parameters is not used, then the vector "p_y" consists of the input Stokes Vector values "s_n", and the elements of the transfer matrix "A", all of which must be defined at each wavelength, This requires at least (4 + (4xn)) x w) calibration parameters, assuming that the ellipsometric parameters (N, C and S), for each calibration sample system are exactly known.

Further, if global parameterization is used, the input vector "s_n" for all wavelengths can be parameterized by the input polarizer azimuth "P", the ellipsometric parameters of the "m" calibration samples can be parametrically calculated as a function of angle of incidence (ϕ_m) and film thickness "t_m", and the transfer matrix "A" can be parameterized by the Azimuth of the analyzer "A", the orientation of each retarder "r_n", and the retardance of each retarder as a function of wavelength

$\delta(\lambda)_n = \delta c_n/\lambda$. It is noted that higher order terms could also be added to the retardance vs. wavelength function, or to any other of the calibration parameters to improve fit between the experimentally measured and modeled generated data. Such a global parameterization significantly reduces the number of calibration parameters required to describe the ($DSP\text{-}SE_{tm}$) system over a spectroscopic range of wavelengths. The total number of calibration parameters in this suggested parameterization (other variations are certainly possible as well), may be as few as:

$$p_y = P + \phi_m + t_m + A + r_n + \delta c_m = 1 + m + m + 1 + n + m = (2 \times m) + (2 \times n) + 2.$$

To extract the ellipsometric parameters of an arbitrary sample system which is inserted into a general ($DSP\text{-}SE_{tm}$) system, a regression analysis can also be performed, and N, C and S can be defined and evaluated by regression at each wavelength separately.

Further, if the plane of incidence of the sample system is allowed to vary slightly, (to account for imperfect alignment to the ellipsometer system), the Stokes Vector which enters the discrete polarization state modifier becomes:

$$M_S \cdot I_P = k \cdot \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(s) & -\sin(s) & 0 \\ 0 & \sin(s) & \cos(s) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(s) & \sin(s) & 0 \\ 0 & -\sin(s) & \cos(s) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} = k \cdot \begin{bmatrix} 1 - s \cdot N \\ -N + s \cdot (1 - C) \\ -s \cdot N + C \\ -S \end{bmatrix}$$

where "s" is the azimuthal misalignment of the sample system, and presumably is very near zero.

In this case the ($DSP-SE_{tm}$) system, would not measure the "true" N, C and S parameters, but would instead measure "effective" parameters Neff, Ceff and Seff:

$$Neff = N - s\cdot(1 - C) \qquad Ceff = C - s\cdot N \qquad Seff = S$$

It would be possible to include the azimuthal misalignment factor "s" as a fitting parameter in subsequent analysis of the ellipsometric data measured by a ($DSP-SE_{tm}$) system.

It is believed that the present invention spectroscopic ellipsometer system combination comprising:

> <u>polarizer and analyzer</u>, (which are both <u>fixed in position during data acquisition</u>); and
>
> at least one <u>stepwise rotatable compensator means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation</u> provided by said source of polychromatic electromagnetic radiation through a plurality of polarization states, said means being present at at least one location selected from the group consisting of:
>
> > between said polarizer and said stage for supporting a sample system; and
> > between said stage for supporting a sample system and said analyzer;

said at least one stepwise rotatable compensator means for discretely, sequentially, modifying a polarization state of a beam of electromagnetic radiation provided by said source of polychromatic electromagnetic radiation through a plurality of polarization states, being positioned so that said beam of electromagnetic radiation transmits therethrough in use;

said system being further characterized by the presence of an Electromagneic Beam Chromatic Shifting and Directing Means being positioned therewithin to receive and reflect electromagnetic radiation with de-emphasized Visual range and emphasized IR and UV range Intensity;

is Patentably distinct over all prior art other than Patents which are co-owned by the J.A. Woollam Co. Inc.

The present invention will be better understood by reference to the Detailed Description Section of this Specification, in combination with the Drawings.

SUMMARY

It is therefore a primary purpose and/or objective of the disclosed invention to teach a simple readily available chromatic shifting and directing means which de-emphasizes intensity at visual wavelengths and emphasizes intensity at IR and UV wavelengths.

It is another primary purpose and/or objective of the disclosed invention to teach provision of at least one chromatic shifting and directing means in an ellipsometer or polarimeter and the like system, the purpose being to de-emphasize intensity at visual wavelengths and emphasize intensity at IR and UV wavelengths, thereby allowing increased spectrometer/detector gain to be applied across the entire spectrum.

It is another purpose and/or objective of the present invention to disclose a spectroscopic ellipsometer system, as well as a method of calibration therefore, which includes provision of polarizer and analyzer elements which are fixed in position during data acquisition procedures, and at least one stepwise rotatable compensator means for imposing a plurality of sequentially discrete, rather than continuously varying, polarization states onto a beam of electromagnetic radiation caused to be present in said spectroscopic ellipsometer system.

It is a specific purpose and/or objective of the disclosed invention to teach a system for and method of applying a Silicon Substrate with between about 500 and 1200 Angstroms of SiO_2 on its surface to accept electromagnetic radiation from a Source thereof, (which provides an output wavelength spectrum comprising relatively high intensity in the visual wavelength range), and

provide electromagnetic radiation with a reflected wavelength spectrum having de-emphasized Visual wavelength intensity and emphasized longer (ie. toward the IR), and into shorter (ie. toward the UV), wavelength intensities.

It is another purpose and/or objective of the disclosed invention to teach ellipsometer/polarimeter systems in which the Silicon Substrate with between about 500 and 1200 Angstroms of SiO_2 on its surface to accept electromagnetic radiation from a Source thereof, (which provides an output wavelength spectrum wherein most the energy is in the visual wavelength range), and provide electromagnetic radiation with a reflected wavelength spectrum having intensity de-emphasized in Visual wavelengths and emphasized in both longer (ie. toward the IR), and shorter (ie. toward the UV), wavelengths.

Other purposes and/or objectives will become clear from a reading of the Specification and Claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1a shows a Beam Chromatic Shifting and Directing Means (ZCM) which comprises a Silicon Substrate (SI) upon the surface of which is present between about 500 and 1500 Angstroms, (nominal 600 or 1200 Angstroms), of Silicon Dioxide (SIO2).

Fig. 1b indicates an incident Electromagnetic Beam (IEM) reflecting from beam chromatic shifting and directing means (ZCM) as beam (OEM).

Fig. 2 demonstrates the effect of reflecting the Energy Spectrum provided by a Spectroscopic Source of Electromagnetic Radiation (ZQTH) off of a Beam Chromatic Shifting and Directing Means (ZCM).

Fig. 3 shows the amount of "P" and "S" Polarization Component Energy, (each relative to a standard "1.0" as input), which reflects from such a Beam Chromatic Shifting and Directing Means (ZCM) as a function of wavelength.

Fig. 4 is included to show results similar to those in Fig. 3, but where only 600 Angstroms of Silicon Dioxide are present on the surface of the Silicon instead of 1200 Angstroms.

Fig. 5, an exemplary specific new design for an ellipsometer/ polarimeter system utilizing a Beam Chromatic Shifting and Directing Means (ZCM).

Figs. 6 - 9 show front elevational views of the new design for an ellipsometer/polarimeter system of Fig. 5 in various states of Spectroscopic Electromagnetic Beam (ZEMI) to Sample (ZS) Angle-of-Incidence (AOI) adjustment.

Figs. 10a - 10e demonstrate functional construction of preferred present invention compensator systems.

Figs. 10f1 - 10l show additional functional construction of compensator systems which are within the scope of the present invention.

Fig. 11 demonstrates the flow of a present invention method of calibration of the spectroscopic ellipsometer portion of the present invention.

Figs. 12-18 show Intensity vs. Wavelength for the seven (7) ellipsometrically different samples, obtained by fitting a mathematical model of the samples and the spectroscopic ellipsometer system by regression onto experimentally obtained data obtained at each of five (5) discrete polarization states.

Figs. 19 & 20 show PSI and DELTA values obtained for samples with thin and thick layers of Oxide thereupon.

Figs. 21 - 23 provide insight to the Psuedo-Achromatic characteristics achieved by a Fig. 10f Compensator design.

DETAILED DESCRIPTION

Turning now to Fig. 1a, thre is shown a Beam Chromatic Shifting and Directing Means (ZCM) which comprises a Silicon Substrate (SI) upon the surface of which is present between about 500 and 1500 Angstroms, (nominal 600 or 1200 Angstroms), of Silicon Dioxide (SIO2). Fig. 1b indicates an incident Electromagnetic Beam (IEM) reflecting from beam chromatic shifting and directing means (ZCM) as beam (EMO).

Fig. 2 demonstrates the effect of reflecting the Energy Spectrum provided by a Spectroscopic Source of Electromagnetic Radiation (ZQTH), (see curve (EMI)) corresponding to Beam (EMI) in Fig. 1b, and the corresponding Shifted Energy Spectrum which results from reflection of said input Spectrum, (see curve labeled (EMO) corresponding to (EMO) in Fig. 1b)), from from a Silicon Substrate upon the surface of which is present Silicon Dioxide (see (ZCM) in Fig. 1b). Fig. 3 shows the amount of "P" and "S" Polarization Component Energy, (each relative to a standard "1.0" as input), which reflects from such a Beam Chromatic Shifting and Directing Means (ZCM) as a function of wavelength. Fig. 4 is included to show results similar to those in Fig. 3, but where only 600 Angstroms of Silicon Dioxide are present on the surface of the Silicon instead of 1200 Angstroms.

Turning now to Fig. 5, an exemplary specific new design for an ellipsometer/polarimeter system is presented as demonstrative of application of the which comprises:

Xenon or Quartz Halogen or the like Source (ZQTH);

Input means (ZINPUT) comprising:

Optical Fiber (ZOF);
Coupler (ZSMA);
Colimating Lens (ZCL);
beam directing mirror (ZM) or beam chromatic shifting and directing means (ZCM), but preferably beam directing mirror (ZM);
Polarizer (ZP1);
First Rotatable Compensator (ZC1);

Sample Supporting Stage;

Output (ZOUTPUT) means comprising:

Second Rotatable Compensator (ZC2);
Analyzer (ZP2);
beam directing mirror (ZM) or preferably beam chromatic shifting and directing means (ZCM);
Focusing Lens (ZFL);
Spectrometer (ZSPEC).

In operation the Xenon or Quartz Halogen or other Source (ZQTH) provides spectroscopic electromagnetic radiation to one end of said Optical Fiber (ZOF), a second end thereof being secured in Coupler (ZSMA). A beam of electromagnetic energy exiting said Coupler (ZSMA) is collimated by Colimating Lens (ZCL) and directed toward a Beam Directing Mirror (ZM), (or a beam chromatic shifting and directing means (ZCM)), from which it reflects. The reflected beam then passes through Polarizer (ZP1) and the First Rotatable Compensator (ZC1) before, as (ZEMI) being caused to impinge upon a Sample (ZS) which is held in position by a Sample Stage (see (ZSTG) in Figs. 6-9).

Electromagnetic radiation (ZEMO) eflects from said Sample (ZS) is directed to pass through Second Rotatable Compensator (ZC2) and Analyzer (ZP2) before being caused to reflect from a Beam Chromatic Shifting and Directing Means (ZCM), (or a Beam Directing Mirror (ZM)). It is noted that the presence of a Beam Chromatic Shifting and Directing Means (ZCM) is a focus of novelty in the disclosed invention. The electromagnetic radiation reflected from said Beam Chromatic Shifting and Directing Means (ZCM) or a Beam Directing Mirror (ZM) is then caused to pass through Focusing Lens (ZFL) and enter Spectrometer (ZSPEC) which is a multi-element detector system. During data acquisition the Polarizer (ZP1) and/or Analyzer (ZP2) and/or Rotatable Compensator (ZC1) and/or Second Rotatable Compensator (ZC2) can be caused to continuously rotate, preferred operation provides that both the Polarizer (ZP1) or Analyzer (ZP2) be held stationary and that one or both of the First Rotatable Compensator (ZC1) and/or Second Rotatable Compensator (ZC2) be sequentially stepped through a progression of discrete polarization state setting positions. While data is collected, no component is moving. In particular this approach eliminates synchronization of rotating element and detector complexity.

Fig. 6 shows a front elevational view indicating incident beam (ZEMI) exits the input means (ZINPUT), reflects off Sample (ZS), and as beam (ZEMO) enter Spectrometer (ZSPEC). Note that the Input Means (ZINPUT) and Output Means (ZOUTPU) each have Fixed Pivots (ZPVI) and Securing Pegs (ZASI) and (ZAS2) respectively. As better viewed in Figs. 7 - 9, Securing Pegs (ZASI) and (ZAS2) allow easily securing Angles-Of-Incidence (AOI) of 65, 70, 75 and 90 degrees (straight-through or Normal by simply removal and re-insertion of the Securing Pegs (ZASI) and (ZAS2) in appropriate holes.

Figs. 10e - 10P demonstrate Compensators for application in

the present invention, and Figs. 14 - 16 show Retardation vs. Wavelength for Compensator designs which are Pseudo-Achromatic.

Figs. 10a, 10b, 10c, 10d and 10e demonstrate that at least one Compensator can be applied as (DSP) or (DSP') in Figs. 1 and 2, which at least one Compensator (DSP) and/or (DSP'), is, in use, rotated about the locus of the electromagnetic beam (EBI) or (EBO), by Compensator Rotation Stepping Means (CSM') and/or (CSM). That is, the presently disclosed invention then comprises a Discrete Polarization State Spectroscopic Ellipsometer System, with the clarification being that the Discrete Polarization State effecting means (DSP) and/or (DSP') is preferably a Rotatable Compensator, which during use is stepped through a plurality of discrete rotation angles, and then held motionless during data acquisition. While not limiting, a utility providing specific embodiment applies Psuedo-Achromatic Rotatable Compensators. (Note, Figs. 14 - 16 show various Psuedo-Achromatic Retardation vs. Wavelength characteristics possible utilizing multiple element compensators, as shown in Fig. 10b).

Further, essentially any Compensator which can be placed into a beam of electromagnetic radiation can be applied, such as those disclosed in Claim 9 of Patent 5,872,630, (which 630 Patent is incorporated by reference hereinto):

Berek-type;
Non-Berek-type;
Zero Order;
Zero Order comprising a plurality of plates;
Rhomb;
Polymer;
Achromatic Crystal; and

Psuedo-Achromatic.

Figs. 10a, 10b, 10c, 10d and 10e demonstrate functional construction of preferred present invention compensator systems. Fig. 10a simply exemplifies that a single plate (SPC) compensator (1) can be applied. Fig. 10b demonstrates construction of a compensator (2) from first (ZO1) and second (ZO2) effectively Zero-Order, (eg. Quartz or Bicrystaline Cadnium Sulfide or Bicrystaline Cadnium Selenide), Waveplates, each of which effective Zero-Order Waveplates (ZO1) & (ZO2) is shown to be constructed from two Multiple Order waveplates, (ie. (MOA1) & (MOB1) and (MOA2) & (MOB2), respectively). The fast axes (FAA2) & (FAB2) of said second effective Zero-Order Waveplate (ZO2) are oriented away from zero or ninety degrees, (eg. in a range around a nominal forty-five degrees such as between forty and fifty degrees), with respect to the fast axes (FAA1) & (FAB1) of said first effective Zero-Order Waveplate (ZO1). In particular Fig. 14b is a cross-sectional side view of a present invention preferred compensator (PC) constructed from a first effective zero-order plate (ZO1) which is constructed from two multiple order plates (MOA1) and (MOB1), and a second effective zero-order plate (ZO2) which is constructed from two multiple order plates (MOA2) and (MOB2). An entered electromagnetic beam (EMBI) emerges as electromagnetic beam (EMBO) with a retardation entered between orthogonal components thereof with a Retardation vs. Wavelength. Figs. 10c and 10d are views looking into the left and right ends of the preferred present invention Compensator (PC) as shown in Fig. 10b, and show that the Fast Axes (FAA2) and (FAB2) of the second effective Zero-Order Waveplate (ZO2) are rotated away from zero or ninety degrees and are ideally oriented at forty-five degrees, with respect to the Fast Axes (FAA1) & (FAB1) of the first effective Zero-Order Waveplate (ZO1). (Note that the fast axis (FAA1) of the first effective Zero-Order Waveplate (ZO1) is shown as a dashed line in Fig. 10d, for reference). Fig. 10e demonstrates functional

construction of another preferred compensator (2') which is constructed from two per se. single plate Zero-Order Waveplates (MOA) and (MOB), which are typically made of materials such as mica or polymer.

(It is specifically to be understood that a present invention compensator system can be comprised of at least one Zero-Order waveplate and at least one effectively Zero-Order waveplate in combination, as well as combinations comprised of two actual Zero-Order waveplates or two effectively Zero-Order waveplates).

Figs. 10f1 - 10l demonstrate additional compensators which can be applied in the present invention.

Fig. 10f1 shows that the first additional present invention retarder system (3) comprises a first triangular shaped element (P1), which as viewed in side elevation presents with first (OS1) and second (OS2) sides which project to the left and right and downward from an upper point (UP1). Said first triangular shaped element (P1) first (OS1) and second (OS2) sides have reflective outer surfaces. Said retarder system (3) further comprises a second triangular shaped element (P2) which as viewed in side elevation presents with first (IS1) and second (IS2) sides which project to the left and right and downward from an upper point (UP2), said second triangular shaped element (P2) being made of material which provides internally reflective, phase delay introducing, interfaces on first (IS1) and second (IS2) sides inside thereof. Said second triangular shaped element (P2) is oriented with respect to the first triangular shaped element (P1) such that the upper point (UP2) of said second triangular shaped element (P2) is oriented essentially vertically directly above the upper point (UP1) of said first triangular shaped element (P1). In use an input electromagnetic beam of radiation (LB) caused to approach said first (OS1) side of said first triangular

shaped element (P1) along an essentially horizontally oriented locus, is shown as being caused to externally reflect from an outer surface thereof and travel along as electromagnetic beam of radiation (R1) which is essentially upwardly vertically oriented. Next said electromagnetic beam of radiation (R1) is caused to enter said second triangular shaped element (P2) and essentially totally internally reflect from said first (IS1) side thereof, then proceed along an essentially horizontal locus and essentially totally internally reflect from the second (IS2) side thereof and proceed along an essentially downward vertically oriented electromagnetic beam of radiation (R3). This is followed by an external reflection from an outer surface of said second side (OS2) of said first triangular shaped element (P1) such that said electromagnetic beam (LB') of radiation proceeds along an essentially horizontally oriented locus, undeviated and undisplaced from the essentially horizontally oriented locus of said input beam (LB) of essentially horizontally oriented electromagnetic radiation. This is the case even when said retarder system (3) is caused to rotate. The result of said described retarder system (3) application being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation (LB). Further, said first (P1) and second (P2) triangular shaped elements are typically right triangles in side elevation as shown in Fig. 10f1, and the outer surfaces of first (OS1) and second (OS2) sides are typically, but not necessarily, made reflective by the presence of a coating of metal thereupon. A coating of metal serves assure a high reflectance and good electromagnetic beam radiation intensity throughput. Also, assuming accurately manufactured right angle first (P1) and second (P2) triangular shaped elements are utilized, this compensator design provides inherent compensation of both angular and translational misalignments of the input light beam (LB). As well, the total retardence provided is compensated for angular misalignments of the input

electromagnetic radiation beam. That is, if the input electromagnetic radiation beam (LB) is not aligned so as to form an angle of incidence of forty-five (45) degrees with the first outer surface (OS1), the reflected electromagnetic beam (R1) will internally reflect at the first internal surface (IS1) of the second triangular shaped element (P2) at a larger (smaller) angle than would be the case if said angle of incidence were forty-five (45) degrees. This effect, however, is directly compensated by a smaller (larger) angle of incidence of electromagnetic beam (R2) where it internally reflects from inner surface (IS2) of the second triangular shaped element (P2). As another comment it is to be understood that because of the oblique angles of incidence of the reflections from the outer surfaces (OS1) and (OS2) of the first triangular shaped element (P1) a polarimeter/ellipsometer in which said compensator (10) is present will require calibration to characterize the PSI-like component thereof.

Fig. 10f2 shows a variation (10') on Fig. 10f1, wherein the first triangular shaped element is replaced by two rotatable reflecting means, identified as (OS1') and (OS2'). This modification allows user adjustment so that the locus of an entering electromagnetic beam (LB') exits undeviated and undisplaced from an entering electromagnetic beam (LB).

Fig. 10g shows that the second additional present invention retarder system (4) comprises a parallelogram shaped element which, as viewed in side elevation, has top (TS) and bottom sides (BS), each of length (d) parallel to one another, both said top (TS) and bottom (NS) sides being oriented essentially horizontally. Said retarder system (4) also has right (RS) and left (LS) sides parallel to one another, both said right (RS) and left (LS) sides being of length ($d/\cos(\alpha)$), where alpha (α) is shown as an angle at which said right (RS) and left (LS) sides project from horizontal. Said retarder system (4) is made of a

material with an index of refraction greater than that of a surrounding ambient. In use an input beam of electromagnetic radiation (LB) caused to enter the left side (LS) of said retarder system (4), along an essentially horizontally oriented locus, is caused to diffracted inside said retarder system (4) and follow a locus which causes it to essentially totally internally reflect from internal interfaces of both said top (TS) and bottom (BS) sides, and emerge from said retarder system (4) as (LB') from the right side (RS) thereof, along an essentially horizontally oriented locus which is undeviated and undisplaced from the essentially horizontally oriented locus of said input beam (LB) of essentially horizontally oriented electromagnetic radiation. This is the case even when said retarder system (4) is caused to rotate. The result of said described retarder system (4) application being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation at said internal reflections from the top (TS) and bottom (BS) surfaces. This retarder system is very robust as it is made of single piece construction. It is noted that adjustment of the angle alpha (α) in manufacture allows setting the amount of retardation which is provided by the retarder system (4). In addition, coatings can be externally applied to top (TS) and bottom surface (BS) to adjust retardation effected by internal reflection from said top (TS) and bottom (BS) surfaces. A formula which defines the retardation provided thereby being:

$$\frac{d}{h} = 2 \cdot \tan(\phi), \text{ where } \phi = \alpha + \sin^{-1}\left(\frac{\sin(90-\alpha)}{n}\right)$$

Fig. 10h shows that the third additional present invention retarder system (5) comprises first (P1) and second (P2)

triangular shaped elements. Said first (P1) triangular shaped element, as viewed in side elevation, presents with first (LS1) and second (RS1) sides which project to the left and right and downward from an upper point (UP1), said first triangular shaped element (P1) further comprising a third side (H1) which is oriented essentially horizontally and which is continuous with, and present below said first (LS1) and second (RS1) sides. Said second triangular shaped element (P2), as viewed in side elevation, presents with first (LS2) and second (RS2) sides which project to the left and right and upward from a lower point (LP2), said second triangular shaped element (P2) further comprising a third side (H2) which is oriented essentially horizontally and which is continuous with, and present above said first (LS2) and second (RS2) sides. Said first (P1) and second (P2) triangular shaped elements being positioned so that a rightmost side (RS1) of said first (P1) triangular shaped element is in contact with a leftmost side (LS2) of said second (P2) triangular shaped element over at least a portion of the lengths thereof. Said first (P1) and second (P2) triangular shaped elements are each made of material with an index of refraction greater than that of a surrounding ambient. In use an input beam (LB) of electromagnetic radiation caused to enter the left (LS1) side of said first (P1) triangular shaped element and is caused to diffracted inside said retarder system (5) and follow a locus which causes it to essentially totally internally reflect from internal interfaces of said third sides (H1) and (H2) of said first (P1) and second (P2) triangular shaped elements, respectively, and emerge from said right side (RS2) of said second (P2) triangular shaped element as electromagnetic radiation beam (LB') which is oriented along an essentially horizontal locus which is undeviated and undisplaced from the essentially horizontally oriented locus of said input beam (LB) of essentially horizontally oriented electromagnetic radiation. This is the case even when said retarder system (5) is caused to

rotate. The result of said described retarder system (5) application being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation (LB). It is noted that as long as the third sides (H1) and (H2) of said first (P1) and second (P2) triangular shaped elements are parallel, the output electromagnetic beam (LB') is undeviated and undisplaced from the input electromagnetic beam (LB) in use. It is noted that The triangular shape elements (P1) and/or (P2) can be made of various materials with various indicies of refraction, and coating(s) can be applied to one or both of the third sides (H1) and (H2) of said first (P1) and second (P2) triangular shaped elements to adjust retardation entered to an electromagnetic beam (LB1).

Fig. 10i shows that the forth additional present invention retarder system (6) comprises a triangular shaped element, which as viewed in side elevation presents with first (LS) and second (RS) sides which project to the left and right and downward from an upper point (UP). Said retarder system (6) further comprises a third side (H) which is oriented essentially horizontally and which is continuous with, and present below said first (LS) and second (RS) sides. Said retarder system (6) is made of a material with an index of refraction greater than that of a surrounding ambient. In use an input beam of electromagnetic radiation (LB) caused to enter the first (LS) side of said retarder system (6) along an essentially horizontally oriented locus, is caused to diffracted inside said retarder system (6) and follow a locus which causes it to essentially totally internally reflect from internal interface of said third (H) side, and emerge from said retarder system (6) from the second (RS) side along an essentially horizontally oriented locus which is undeviated and undisplaced from the essentially horizontally oriented locus of said input beam of essentially horizontally oriented electromagnetic radiation (LB). This is the case even

when said retarder system (6) is caused to rotate. The result of said described retarder system (6) application being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation (LB). The Fig. 10i retarder system (6) is typically an isosceles prism which is available off-the-shelf with an angle alpha (α) of forty-five (45) degrees. As long as the input electromagnetic beam (LB) height (h) is chosen in accordance with the formula:

$$d = 2h\left(\frac{1}{\tan(\alpha)} + \tan(\phi)\right), \text{ where } \phi = \alpha + \sin^{-1}\left(\frac{\sin(90-\alpha)}{n}\right)$$

in conjunction with the index of refraction (n) of the material from which the retarder system (6) is made, and the locus of the input electromagnetic radiation beam (LB) is parallel with the third side (H) of said retarder system (6), the output electromagnetic beam (LB') will not be deviated or translated with respect to the input electromagnetic beam (LB). As well, note the dashed line (DL) below the upper point (UP). This indicates that as the region above said dashed line (DL) is not utilized, the portion of said retarder system (6) thereabove can be removed. It is also noted that the input electromagnetic beam (LB) enters and exits the retarder system (6) other than along a normal to a surface thereof, said retarder system is not an ideal retarder with a PSI of forty-five (45) degrees. It is noted that the third side (H) of the retarder system (6) can be coated to change the retardation effects of an internal reflection of an electromagnetic beam of radiation therefrom, and such a coating can have an adverse effect on the nonideal PSI characteristics.

Fig. 10l shows that the fifth additional present invention retarder system (7) comprises first (PA1) and second (PA2)

parallelogram shaped elements which, as viewed in side elevation, each have top (TS1)/(TS2) and bottom (BS1)/(BS2) sides parallel to one another, both said top (TS1) (TS2) and bottom (BS1) (BS2) sides each being oriented at an angle to horizontal. Said first (PA1) and second (PA2) parallelogram shaped elements also each have right (RS1)/(RS2) and left (LS1)/(LS2) sides parallel to one another, all said right (RS1) (RS2) and left (LS1) (LS2) sides being oriented essentially vertically. Said first (PA1) and second (PA2) parallelogram shaped elements are made of material with an index of refraction greater than that of a surrounding ambient. A right most vertically oriented side (RS1) of said first parallelogram is in contact with a leftmost (LS2) vertically oriented side of the second parallelogram shaped element (PA2). In use an input beam of electromagnetic radiation (LB) caused to enter an essentially vertically oriented left side (LS1) of said first parallelogram shaped element (PA1) along an essentially horizontally oriented locus, is caused to be diffracted inside said retarder system and follow a locus which causes it to essentially totally internally reflect from internal interfaces of both said top (TS1) (TS2) and bottom (BS1) (BS2) sides of both said first and second parallelogram shaped elements (PA1) (PA2), then emerge from a right side (RS2) of said second parallelogram shaped element (PA2) along an essentially horizontally oriented locus as output beam of electromagnetic radiation (LB') which is undeviated and undisplaced from the essentially horizontally oriented locus of said input beam of essentially horizontally oriented electromagnetic radiation (LB). This is the case even when said retarder system (7) is caused to rotate. The result of said described retarder system (7) application being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation (LB).

Fig. 10j1 shows that the sixth additional present invention retarder system (8) comprises first (BK1) and second (BK2)

Berek-type retarders which each have an optical axes essentially perpendicular to a surface thereof. As shown by Fig. 10j2, each of said first (BK1) and second (BK2) Berek-type retarders can have fast axis which are oriented other than parallel to one another, but for the presently described retarder system it is assumed that the fast axes are aligned, (ie. an angle PHI ( ) of zero (0.0) degrees exists between fast axes of the two Berek-type (BK1) and (BK2) plates in Fig. 10j1. Said first and second Berek-type retarders each present with first and second essentially parallel sides. Said first (BK1) and second (BK2) Berek-type retarders are oriented, as viewed in side elevation, with first (LS1) and second (RS1) sides of one Berek-type retarder (BK1) being oriented other than parallel to first (LS2) and second (RS2) sides of the other Berek-type retarder (BK2). In use an incident beam of electromagnetic radiation (LB) is caused to impinge upon one of said first (BK1) Berek-type retarder on one side (LS1) thereof, partially transmit therethrough then impinge upon the second Berek-type retarder (BK2), on one side thereof (LS2), and partially transmit therethrough such that a polarized beam of electromagnetic radiation (LB') passing through both of said first (BK1) and second (BK2) Berek-type retarders emerges from the second thereof in a polarized state with a phase angle between orthogonal components therein which is different than that in the incident beam of electromagnetic radiation (LB), and in a direction which is an essentially undeviated and undisplaced from the incident beam of electromagnetic radiation. This is the case even when said retarder system (8) is caused to rotate. The result of said described retarder system (8) application being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation. For insight it is mentioned that, in general, a Berek-type retarder is a uniaxial anisotropic plate with its optical axis essentially perpendicular to a surface thereof. The retardence introduced to an

electromagnetic beam caused to transmit therethrough is determined by a tipping of said plate. The retardation system (8) having two such Berek-type retarders present, is, it is noted, insensitive to small angular deviations in an input electromagnetic beam as each plate contributes approximately hal of achieved retardence. This insensitivity results because if the input electromagnetic beam is slightly changed, one of said plates will contribute slightly more (less), but the second slightly less (more) retardence because of offsetting effective plate "tilts" with respect to electromagnetic beams input thereto. Also, said retarder system (8) is very nearly ideal in that the PSI component of the retarder system (8) is very near a constant forty-five (45) degrees. One problem however, is that Berek-type retarder plates exhibit a (1/wavelength) retardence characteristic which, without more, makes use over a wide spectral range difficult.

A variation of the just described retarder system (8) applies to the seventh additional present invention retarder system (9) as well, with the difference being that a Fig. 10j2 offset angle PHI (ϕ) other than zero (0.0) is present between fast axes of the two Berek-type plates. The description of the system remains otherwise unchanged. The benefit derived, however, is that a flatter than (1/wavelength) retardation characteristic can be achieved thereby.

Fig. 10k1 serves as the pictorial reference for the eighth additional present invention retarder system (10) which comprises first (BK1), second (BK2), third (BK3) and forth (BK4) Berek-type retarders which each have an optical axes essentially perpendicular to a surface thereof, each of which first (BK1) and second (BK2) Berek-type retarders has a fast axis, said fast axes in said first (BK1) and second (BK2) Berek-type retarders being oriented essentially parallel to one another. This is

exemplified by Fig. 10k2. Said first (BK1) Berek-type retarder presents with first (LS1) and second (RS1) essentially parallel sides and said second (BK2) Berek-type retarders each present with first (LS2) and second (RS2) essentially parallel sides, and said first (BK1) and second (BK2) Berek-type retarders are oriented, as viewed in side elevation, with first (LS1) and second (RS1) sides of said first Berek-type retarder being oriented other than parallel to first (LS2) and second (RS2) sides of said second (BK2) Berek-type retarder. In use an incident beam of electromagnetic radiation (LB) is caused to impinge upon said first (BK1) Berek-type retarder on said first side (LS1) thereof, partially transmit therethrough then impinge upon the second (BK2) Berek-type retarder, on said first (LS2) side thereof, and partially transmit therethrough such that a polarized beam of electromagnetic radiation (LB') passing through both of said first (BK1) and second (BK2) Berek-type retarders emerges from the second thereof in a polarized state with a phase angle between orthogonal components therein which is different than that in the incident beam of electromagnetic radiation (LB), and in a direction which is an essentially undeviated and undisplaced from the incident beam of electromagnetic radiation (LB). Each of which third (BK3) and forth (BK4) Berek-type retarders also has a fast axis, and said fast axes in said third (BK3) and forth (BK4) Berek-type retarders are oriented essentially parallel to one another but other than parallel to the parallel fast axes of said first (BK1) and second (BK2) Berek-type retarders. Said third (BK3) Berek-type retarder presents with first (LS3) and second (RS3) essentially parallel sides, and said forth (BK4) Berek-type presents with first (LS4) and second (RS4) essentially parallel sides, and said first third (BK3) and forth (BK4) Berek-type retarders are oriented, as viewed in side elevation, with first (LS3) and second (RS3) sides of one of said third (BK3) Berek-type retarder being oriented other than parallel to first (LS4) and second (RS4) sides of said

forth (BK4) Berek-type retarder; such that in use an incident beam of electromagnetic radiation (LB') exiting said second (BK2) Berek-type retarder is caused to impinge upon said third (BK3) Berek-type retarder on said first (LS3) side thereof, partially transmit therethrough then impinge upon said forth (BK4) Berek-type retarder on said first (LS4) side thereof, and partially transmit therethrough such that a polarized beam of electromagnetic radiation (LB'') passing through said first (BK1), second (BK2), third (BK3) and forth (BK4) Berek-type retarders emerges from the forth (BK4) thereof in a polarized state with a phase angle between orthogonal components therein which is different than that in the incident beam of electromagnetic radiation (LB) caused to impinge upon the first (LS1) side of said first (BK1) Berek-type retarder, in a direction which is an essentially undeviated and undisplaced from said incident beam of electromagnetic radiation (LB). This is the case even when said retarder system (8) is caused to rotate. The result of said described retarder system (8) application being that retardation is entered between orthogonal components of said input electromagnetic beam of radiation.

A ninth additional present invention retarder system (11) is also pictorially represented by Fig. 10k1 and is similar to that just described excepting that the Berek-type retarder plates (BK1) and (BK2) fast axes need not be parallel to one another and the Berek-type retarder plates (BK3) and (BK4) need not be parallel to one another. However, if as a group Berek-type retarder plates ((BK1) and (BK2))/((BK3) and (BK4)) are parallel, they can be, but need not be parallel the fast axes of Berek-type retarder plates ((BK3) and (BK4))/((BK1) and (BK2)). This embodiment includes the case where all the fast axes of all Berek-type retarders (BK1), (BK2), (BK3) and (BK4) are all different.

Further, as described in the Disclosure of the invention Section of this Specification, as the polarizer in the present invention spectroscopic ellipsometer system remains fixed in position during data acquisition, it is preferable that a source of electromagnetic radiation, and/or a present Polarizer or Polarization State Generator be positioned or configured so as to pass predominately "S" Polarized electromagnetic radiation, as referenced to said beam combining system. The reason for this is that the split between transmission and reflection "S" polarization components is less, as a function of wavelength and electromagnetic beam angle-of-incidence to said beam combining means, compared to that between the "P" components.

It is noted that any of said sources (S1) (S2) and (S3) of polychromatic electromagnetic radiation can be Xenon or Duterium, and Quartz-Halogen lamps, or other suitable source.

It is also noted that a suitable electromagnetic beam combining (BCM) means can be made of glass or a fused silica plate, (preferably uncoated), and can also be "Hot Mirrors" which reflect IR and transmit visual wavelengths, or "Cold Mirrors" which reflect visible and transmit IR; mirror-type Beamsplitters or Pellicle Beamsplitters, such as described in Edmund Industrial Optics Catalog Number N997A.

It is also generally noted that the present invention spectroscopic ellipsometer system can, but not necessarily, utilize Zeiss Diode Array Spectrometer Systems identified by manufacturer numbers in the group: (MMS1 (1000-1150 nm); UV/VIS MMS (190-7100 nm); UV MMS (190-400 nm); and IR MMS (900-2400 nm)) as Detector System (DET). Said identified Zeiss systems provide a very compact system comprising a multiplicity of Detector Elements and provide focusing via a Focusing Element, Slit, and

single concave holographic grating dispersive optics. However, any functional multi-element spectroscopic Detector arrangement is within the scope of the present invention.

Contuinuing, Fig. 11 demonstrates the flow of a present invention method of calibration of the spectroscopic ellipsometer portion of the present invention.

Figs. 12-18 show Intensity vs. Wavelength for the seven (7) ellipsometrically different samples at each of five (5) imposed polarization states. Results shown in Figs. 5 - 7 respectively, are for Samples identified as 1, 2, 3, 4, 5, 6, and 7, which respectively have Oxide depths atop thereof of, (in Angstroms), 17.50; 103.0; 193.0; 508.0; 1318.0; 4817.0 and 9961.0.

Figs. 19 & 20 show PSI and DELTA values obtained for samples with thin (native), and thick, (9961 Angstrom), layers of Oxide thereupon. All results were obtained by fitting a mathematical model of the sample system and the spectroscopic ellipsometer system by regression onto experimental data.

Figs. 21 - 23 are also included herein to provide insight to the Psuedo-Achromatic characteristics achieved by the Fig. 10f Compensator design. Fig. 21 shows a plot of such a compensator retardation characteristic which depends as (1/wavelength), (dashed line), as well as a present invention compensator charactristic, (solid line). The important thing to note is that a selected range of wavelengths over which a retardation of between seventy-five (75) and one-hundred-thirty (1100) degrees is developed, is much greater for the present invention compensator. A present invention spectroscopic rotatable compensator ellipsometer system can comprise at least one compensator(s) which produces a retardance of, preferably, between seventy-five (75) and one-hundred-thirty (1100) degrees

over a range of wavelengths defined by a selection from the group consisting of:

a. between one-hundred-ninety (190) and seven-hundred-fifty (750) nanometers;

b. between two-hundred-forty-five (245) and nine-hundred (900) nanometers;

c. between three-hundred-eighty (1080) and seventeen-hundred (1700) nanometers;

d. within a range of wavelengths defined by a maximum wavelength (MAXW) and a minimum wavelength (MINW) wherein the ratio of (MAXW)/(MINW) is at least one-and-eight-tenths (1.8).

Acceptable practice however, provides for the case wherein at least one of said at least one compensator(s) provides a retardation vs. wavelength characteristic retardation between thirty (30.0) and less than one-hundred-thirty-five (135) degrees over a range of wavelengths specified from MINW to MAXW by a selection from the group consisting of:

a. MINW less than/equal to one-hundred-ninety (190) and MAXW greater than/equal to seventeen-hundred (1700);

b. MINW less than/equal to two-hundred-twenty (220) and MAXW greater than/equal to one-thousand (1000) nanometers;

c. within a range of wavelengths defined by a

maximum wavelength (MAXW) and a minimum wavelength (MINW) range where (MAXW)/(MINW) is at least four-and one-half (4.5).

(NOTE, the specified vales and ranges can not be achieved by single plates with (1/wavelength) retardation characteristics).

More specifically, Fig. 22 shows calculated retardation vs. wavelength curves for two compensators which demonstrate (1/wavelength) retardation characterics, (long and short dashed lines), and the retardation curve, (solid line), of a present invention assembly configuration as demonstrated in Fig. 10f which is arrived at by combining said two retarders with a 45 degree angle between the fast axes thereof. Fig. 23 shows a re-scaled plot of the solid line curve shown in Fig. 22.

Having hereby disclosed the subject matter of the present invention, it should be obvious that many modifications, substitutions, and variations of the present invention are possible in view of the teachings. It is therefore to be understood that the invention may be practiced other than as specifically described, and should be limited in its breadth and scope only by the Claims.